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Abstract

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I will describe only a couple of the facets of the current NOT program at NBS. The program is growing, and by now is approaching the size of about 3/4 of a million dollars per year. The aim of the program is to bring direct impact on nondestructive activities through better test methods, through standards, and through measurement services and interpretive methodologies.

I will describe progress on an activity aimed at near term improvements in ASTM type reference blocks and also on an effort aimed at producing characterized flaws. I will also very briefly touch on some work we are doing towards establishing measurement techniques for determining the characteristics of ultrasonic and acoustic emission transducers. The ASTM reference block work is supported by the Air Force, NASA and the Army, and the work on characterized flaws and transducers is supported by in-house funding.

Disciplines

Materials Science and Engineering | Structures and Materials

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ULTRASONIC REFERENCE BLOCKS AND
CHARACTERIZED FATIGUE CRACKS

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Washington, D.C.

The National Bureau of Standards initiated an identifiable program in nondestructive testing about a year and a half ago. Up until that time there was significant effort in areas affecting NDT, but the focus of these efforts was not nondestructive testing.

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When we started the program we had the necessary technical competence but little background and even less equipment in the area of ultrasonic nondestructive testing. In addition to developing background information it was necessary to develop an operational ultrasonic test bench. Our current laboratory set-up is shown in Fig. 1. It consists of an immersion tank, spectrum analyzer, commercial-type flaw detector, and a laboratory-type flaw detector with several modules, including a linear gate and peak detector quantizer. It also includes a wide band oscilloscope and some electronics necessary for n-level gray-tone recording.

First focusing on the work on the ASTM ultrasonic reference blocks, I show in Fig. 2 the block geometry spelled out by ASTM documents E-127 and E-428. Simply, the reference blocks are right circular cylinders with a hole drilled along the axis, the hole being a flat bottomed hole. Of course, the flat bottomed hole becomes a reflector, and the energy returned to a transducer from this reflector is used to check the performance of inspection equipment and used to determine test sensitivity and rejection levels . Sets of the reference blocks consisting of different metal travel distances and different hole diameters are used, usually in the material of choise, but most often in aluminum, titanium or steel.

The problem very simply stated is this: using one ultrasonic measuring system, one obtains unacceptably different ultrasonic responses from nominally

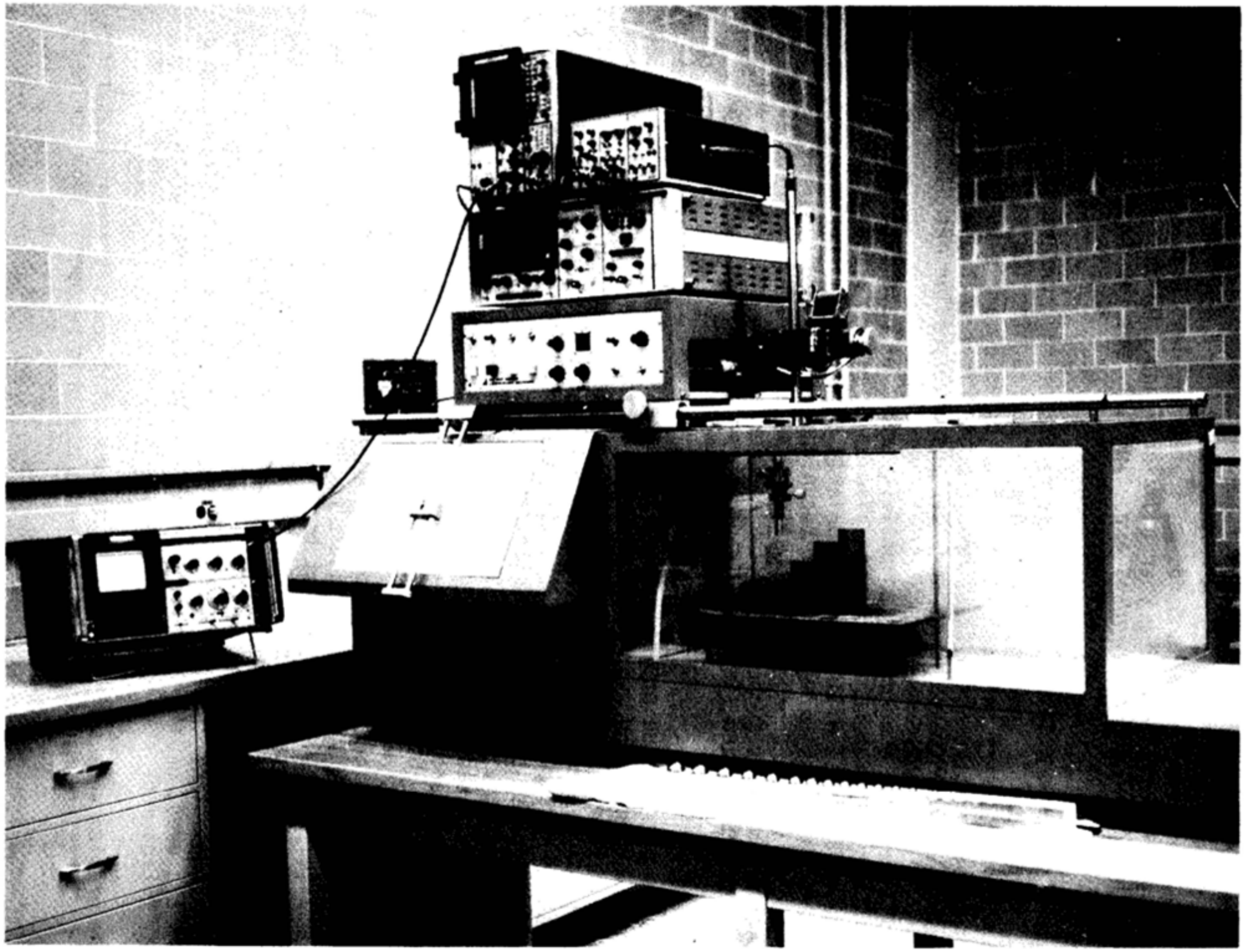


Fig. 1. Ultrasonic measurement facility

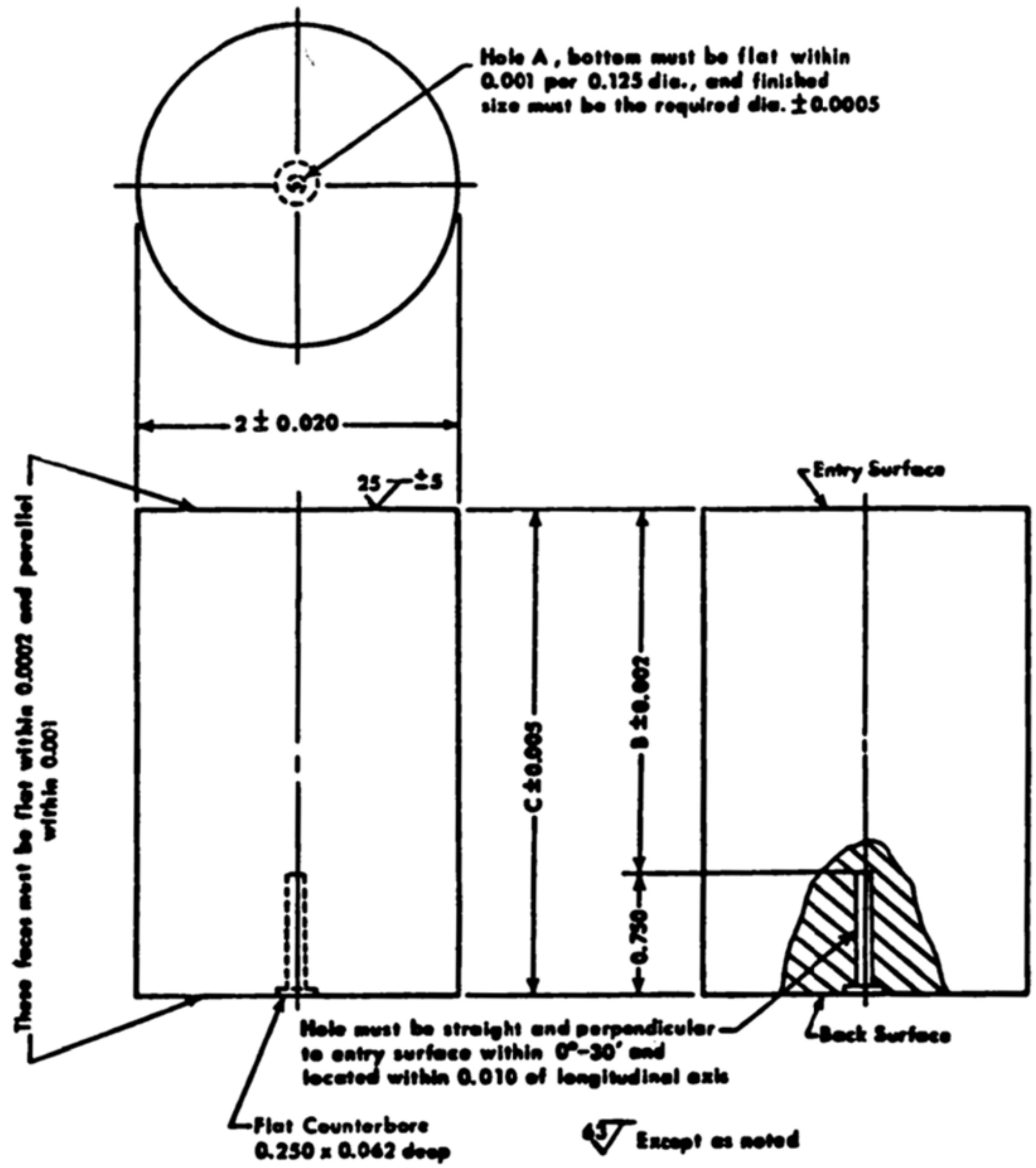


Fig. 2. ASTM E-127 ultrasonic standard reference block. All dimensions in inches (1 in. = 25.4 mm).

identical reference blocks. The goal of the project is to affect a near term improvement in the variability of this ASTM-type block, that is, to decrease the difference in response between nominally identical blocks. Our first-year effort on this program is described in detail in Ref. 1.

One of the first major objectives was to quantify this block-to-block variability in response. So far we've taken data on about 25 sets of blocks from the field. They have been examined at 2 1/4, 5 and 10 MHz and recordings made of both the RF waveform and the frequency spectrum of the received signal. Figure 3 is a plot of some of that data. It shows the amplitude of the ultrasonic response of reference blocks versus metal travel distance for a number of sets. By now we have data on quite a number of sets in addition to that shown in Fig. 3. The amplitude of response of many of the blocks is in an average error band of, say, 20 to 30 percent. However, the response from the one set designated as No s/n is consistently very high, with differences in response between blocks of this set and nominally identical blocks reaching approximately 800 percent. Trying to set up a measurement system with standards that vary by 800 percent is a standards horror story as far as we're concerned. At this point in the program, we can isolate a significant part of the 800 percent variation in response. We can say some large but unknown percentage of the error is due to differences in the block metallurgy. And we can say that 800 minus x is due to some other causes, but we haven't yet pinned down exactly what x is. It's at least several hundred percent.

It turns out that this particularly deviant set was made by one of the leading manufacturers of reference blocks and was made from stock produced in about 1964 by one of the leasing aluminum companies. During that year their rod producing plant was down for some reason. The material was sold as rolled rod but actually was made by more of a drawing operation. This drawn material made it to the market marked as "rolled rod" and blocks were made out of it and sold. Recently, the aluminum company has done confirmation experiments and they get, roughly, the kind of data shown in Fig. 3 on blocks that they made from material that they have saved from the 1964 lot. It is not clear that this mislabeling problem is over since a warehouser could unknowingly still have some of the 1964 material on the shelf. Additionally one must be concerned with the problem of gradual changes that have occurred in 7075 aluminum alloy as was pointed out by Mr. Stellabotte (in previous discussion). If one compares 1950 material with 1975 material, one finds distinct differences in the characteristics of the 7075 alloy.

At NBS, considerable metallurgical effort has been performed on reference blocks and block material. This work is being done by Dr. A. W. Ruff and G. J. Bechtoldt in the Metallurgy Division. Part of this work involves a rather careful look at several blocks that were rejected during manufacture by the fabricator. Sections of these rejected reference blocks were interrogated ultrasonically. Monitoring the back surface reflection we could find differences in amplitude of response of up to 75 percent at different points in a specimen that was about an inch and a half thick. These areas of significantly different ultrasonic response have been correlated pretty reasonably with differences in metallurgical structure

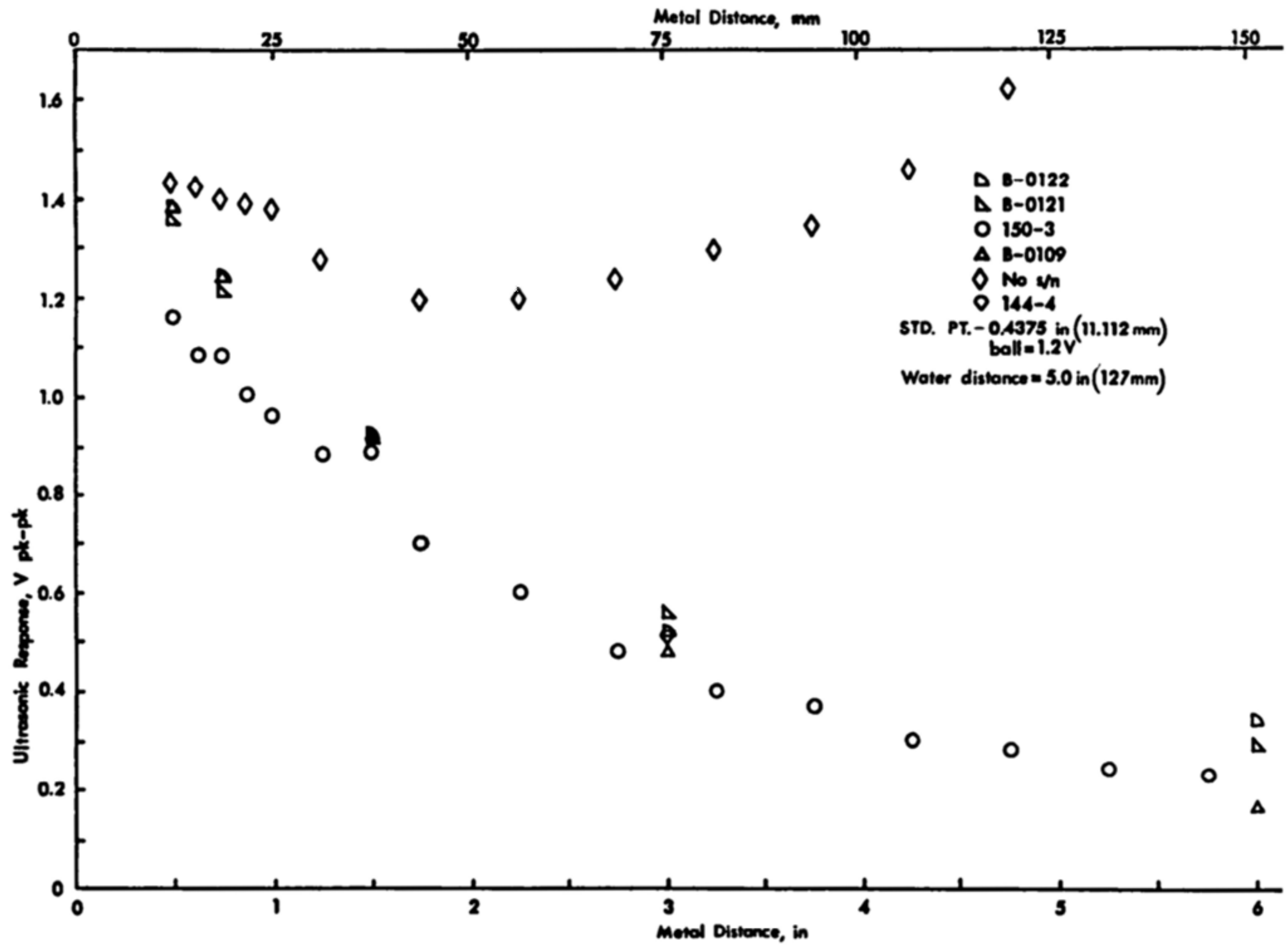


Fig. 3. Distance-amplitude data for No. 5 blocks at 5.0 MHz.

at different points in the block. Significant variations in residual stress were measured, and metallurgically, the material is very messy, particularly in the center. There are voids, foreign phase regions, inclusions, chemical concentration variations, and possibly most importantly, a good deal of solidification structure near the center remaining from that initial ingot solidifications.

As part of an effort to determine the effects of the fabrication process of reference blocks on their ultrasonic response, we have fabricated 30 blocks at NBS. We gave the machinist the drawing from the ASTM E-127 document with no additional instructions. The material we provided was 7075-T651 extruded rod, primarily because we had a good ready supply from a single run. Table I shows some of the results from some of these blocks manufactured at NBS. At 5 MHz, the differences in response between nominally identical blocks are all less than 7 percent; at 2 1/4 MHz it is significantly less than that; at 10 MHz it's somewhat greater.

Subsequent to these measurements we made another dozen blocks. Four number 3, 5, and 8 blocks were made all with a 2 3/4 inch metal travel distance (see Fig. 2). After they had been machined up to the point of putting the flat bottomed hole in, the amplitude of the ultrasonic response from the back surface was checked. The amplitudes of the back reflection from any of the 12 cylinders differed by at most 10 percent. We then ordered the blocks in terms of this back reflection so that each size hole would be made from blocks with the maximum spread in terms of back reflection. Then the holes were put in and they were checked for the ultrasonic response of the flat bottomed hole. The variation in response of the flat bottomed holes was less than about 10 percent when checked at 2 1/4, 5, 10, and 15 MHz. One then must ask, "Is this machinist so good that he's performing to a much better tolerance than is specified by E-127, or is the problem obviously metallurgy, which has been eliminated as a variable in this study?". If the former is the case, then we might end up with a goldplated machinist, which really isn't satisfactory.

Several other activities related to fabrication are in progress. These include additional work on dimensional metrology and a study of the feasibility of non-conventional fabrication methods such as the use of two piece blocks joined in an ultrasonically transparent manner. Work in these areas is well along, but we are not prepared to report data yet. Other areas that require additional work include the metallurgy of steel and titanium block stock and the data base on the response of steel and titanium reference blocks now being used in the field.

Some of the possible output forms for this project are shown in Fig. 4. If a technique is developed for producing blocks that requires only normal skill, it would be feasible to produce a document to describe a method for the user community to produce the blocks. However, if a technique is developed that requires very special care, then the approach might be to produce and market the blocks under the auspices of NBS similar to the way NBS produces and sells standard reference materials. If no acceptable technique for making

Table I. Ultrasonic Response of NBS Homemade 7075-T651 Blocks.

Block Size and Number	Ultrasonic Response (volts) Test Frequency (MHz) 2.25	5.0	10.0	15.0
5-0050-1	1.00	1.00	0.500	0.300
-2	1.02	1.00	0.530	0.320
-3	1.02	1.02	0.530	0.325
-4	1.02	1.02	0.530	0.315
-5	1.05	1.01	0.540	0.300
-6	1.03	0.99	0.500	0.270
5-0300-1	1.19	0.450	0.500	0.245
-2	1.27	0.475	0.550	0.305
-3	1.30	0.480	0.570	0.325
-4	1.22	0.455	0.500	0.250
-5	1.20	0.425	0.470	0.225
-6	1.20	0.420	0.480	0.240
5-0575-1		1.32		
-2		1.30		
-3		1.40		
-4		1.34		
-5		1.40		
-6		1.30		

1. NEW METHODS DOCUMENT TO IMPROVE OR REPLACE E127 AND E428

2. CERTIFIED REFERENCE BLOCKS SOLD BY NBS AS " STANDARD REFERENCE MATERIALS "

3. NBS MAINTAINS " GOLD-PLATED " BLOCKS AND OFFERS CALIBRATION SERVICE

Fig. 4. Output of NBS effort on ASTM type reference blocks.

consistant blocks is found, we might have to revert to the "British system". This system defines a "gold-plated" set of blocks and requires some technique for comparing the response of those blocks to user's blocks.

I would like to shift your attention to the area of well characterized flaws. A standards goal in the future might be a set of standard flaws. This seems at this point, very difficult to attain. So, the next best thing, possibly, is to develop well characterized flaws. The difference is that you don't require the artifacts to be the same but you have determined the amounts of and causes for the differences. The initial focus in this work is on fatigue cracks since they are the most frequent object of search in service inspection. The starting point for this work was the ASTM E-399 compact tension (CT) specimen. The reason for choosing this specimen is that this geometry gives us a good deal of fracture mechanics background for mechanical compliance measurements, stress intensity factor calculations, etc., that are necessary to characterize certain features of the fatigue cracks.

A partial listing of some of the factors affecting the ultrasonic response of fatigue cracks is given in Fig. 5. The intent is to control as many of these factors as possible and to characterize the effect on ultrasonic response of the remainder. Several of the variables are controlled, at least nominally, by the loading program used to produce the crack. However, at least the effects of stress intensity or applied stress at the crack and relative geometry of transducer and crack will have to be quantitatively determined after the production of the cracks.

Figure 6 is a drawing of the E-399 CT specimen. After producing cracks that we feel are nominally identical, we will verify how well we have done by measuring the crack size and shape. About six different techniques are being evaluated for such measurements. These are listed in Fig. 6; crack opening displacement, ultrasonic indexing, surface microscopy, ultrasonic C-scan, acoustical holography, neutron radiography, and finally, rather detailed metallographic studies of the fracture surface after the specimen has been fast fractured.

Two of these techniques are shown schematically in Fig. 6, the compliance method which is quite standard, and also the ultrasonic indexing. For the indexing there is a contact transducer located on top of the specimen, and the transducer is positioned so that its radiated field is just barely interrupted by the tip of the crack. Then by moving the transducer with a micrometer screw so a constant ultrasonic response is obtained, one can obtain, through the micrometer readings, a measurement of how far the crack has progressed. This technique was primarily developed by Clark and Cheschini at Westinghouse[2].

The acoustical holography is being done on contract outside NBS. This work is in progress. We have received a preliminary report, but have not yet received the final data necessary for correlation with the other techniques. The neutron radiography is being done by Harry Berger and coworkers at the NBS reactor. The intent is to introduce a solution with a high neutron cross section into the crack and then portray the profile of the crack through a neutron radiograph.

1. **SIZE**
2. **SHAPE**
3. **LOCATION**
4. **ORENTATION**
5. **RESIDUAL STRESS (CLOSURE)**
6. **SURFACE FINISH (STRIATIONS)**
7. **APPLIED STRESS (OR STRESS INTENSITY)**

Fig. 5. Factors affecting ultrasonic response from fatigue cracks.

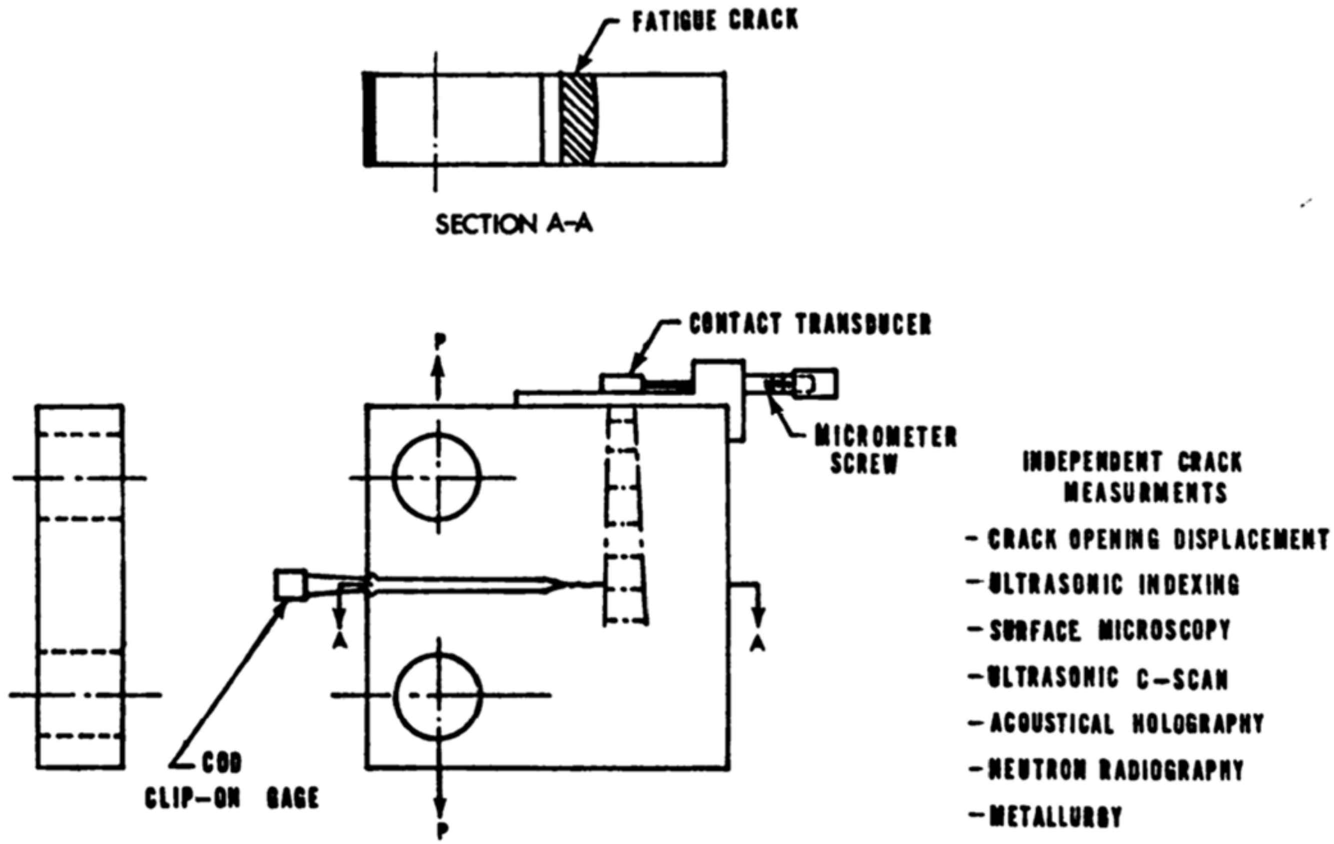


Fig. 6. ASTM E-399 Compact tension specimen.

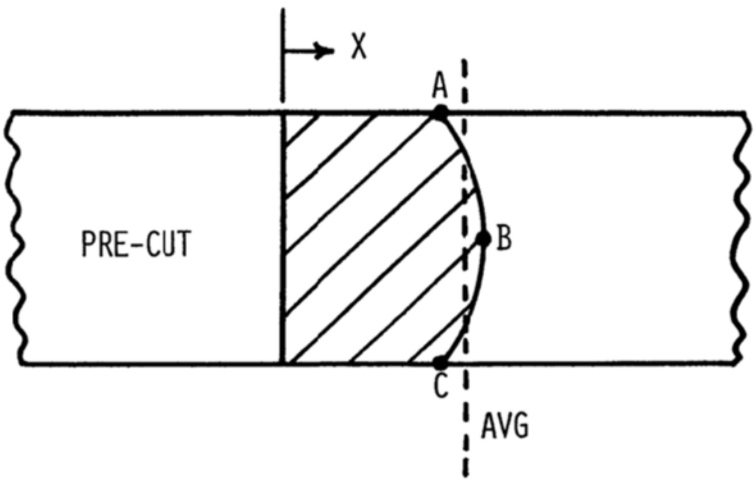
Figure 7 shows the correlation of some of the measurements on one specimen. The surface microscopy describes points A and C. We usually use a liquid penetrant to assist in that measurement. Ultrasonic indexing pretty well describes point B, the tip of the crack profile. The COD compliance measurement, in the words of George Irsin, "Gives you the length of the crack the specimen thinks it has." It is an average crack measurement. This measurement is also used for control during the fatigue cracking. We've also developed a quantitative C-scan method for profiling the cracks, and that data is listed in Fig. 7 also. We are holding back on the fractographic analysis until we can get data on the specimen using neutron radiographic and holographic methods.

As soon as we've fully correlated data on some additional specimens and determined the final methods of choice for determining when a specimen is, in fact, very close to its nominally identical specimens in terms of crack length, shape and surface, we'll move rather quickly into characterizing the effects of applied stress and relative geometry between the crack and transducer on the ultrasonic response.

Now, the other area I wanted to touch on briefly is the work on the calibration of ultrasonic and acoustic emission transducers. This work is being done by Mo Greenspan, Frank Breckenridge and Carl Tschiegg at NBS.

For ultrasonic transducers, they have developed a modulated swept CW technique for exciting ultrasonic transducers and a nulled sensor which picks up the total radiated power of these transducers. The intent is to produce a measurement technique for obtaining absolute mechanical power output versus frequency for ultrasonic transducers. This work is under way and the system is being refined at this point. We've measured relative power versus frequency on a number of transducers. These were purchased from the commercial market. We have taken data on about 12 transducers and the data from two of them (Fig. 8 and 9) were rather interesting. The break in the response at 10 and 20 MHz is simply a matter of resetting the sweep generator. The transducer whose response is shown in Fig. 8 is nominally a 10 MHz center frequency transducer, and, in fact, the center frequency is pretty close to 10 MHz, but there is a very interesting bump at 5 MHz. It's not clear how one takes this kind of thing into account if, for example, one were working with rather frequency dependent materials. I would think that one would at least want to know about such behavior. Fig. 9 shows the power curve for a transducer with a nominal 15 MHz center frequency, but the measured center frequency was more like 23 MHz. These are 2 out of just 12 transducers so we didn't have too much trouble finding anomalous ones.

There is some additional work on transducers that Greenspan et al are involved in. This was motivated by work on pure acoustic emission source signals. Their experimental setup is detailed in Fig. 10. They've developed a method for producing a step function in force and have also developed a very broad band capacitance-type receiver. The idea is to make use of this set up for measuring certain characteristics of acoustic emission transducers[3].



CRACK LENGTH (INCHES)

	A	B	C
SURFACE MICROSCOPY	0.621	-	0.521
ULTRASONIC INDEXING	-	0.787	-
COD - COMPLIANCE	←	0.720	→
ULTRASONIC C-SCAN	0.67	0.77	0.58
NEUTRON RADIOGRAPHY			
ACOUSTIC HOLOGRAPHY			
FRACTOGRAPHIC ANALYSIS			

Fig. 7. Correlation of crack measurements for specimen 6-CT-12.

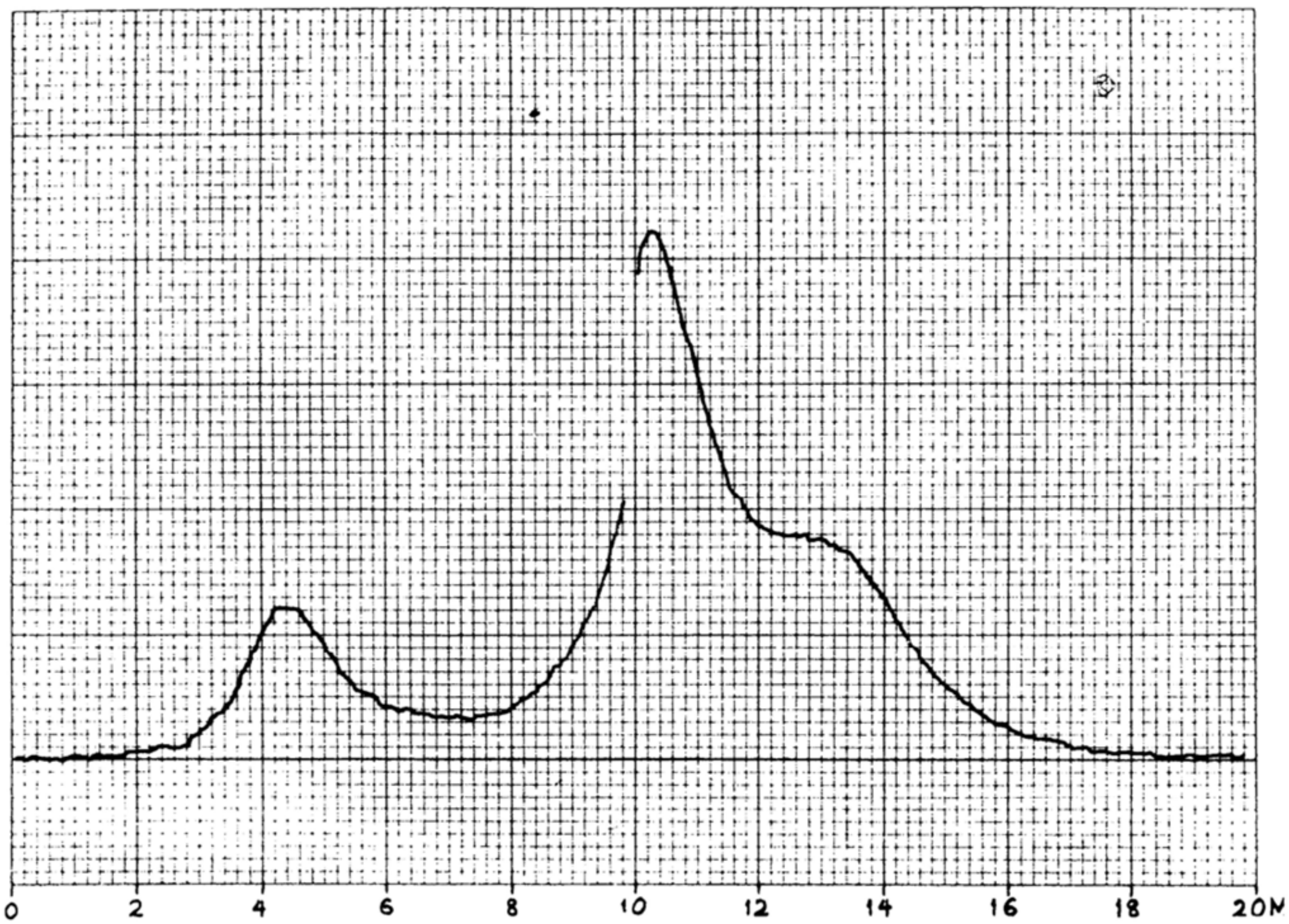


Fig. 8. Total power versus frequency for a nominal 10 MHz transducer.

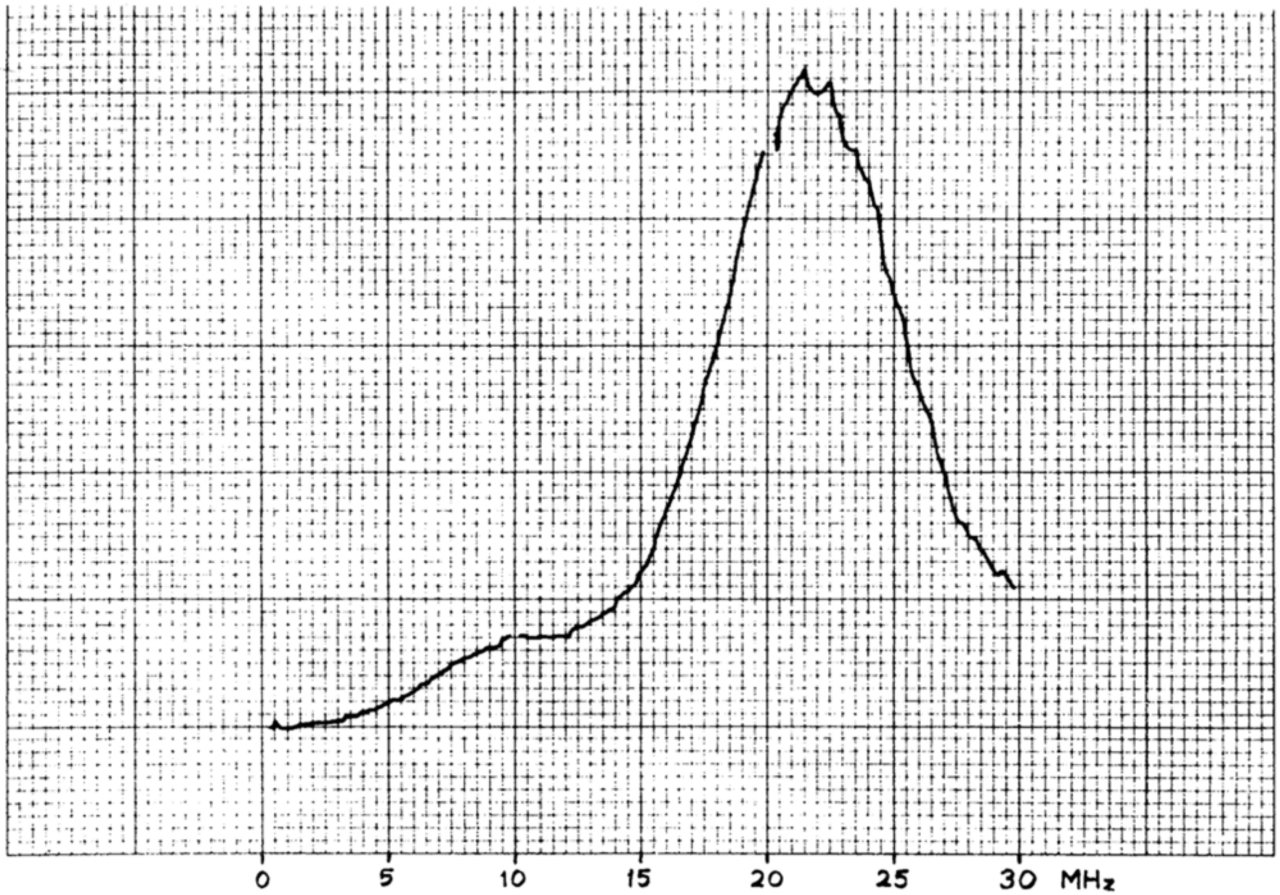


Fig. 9. Total power versus frequency for a nominal 15 MHz transducer.

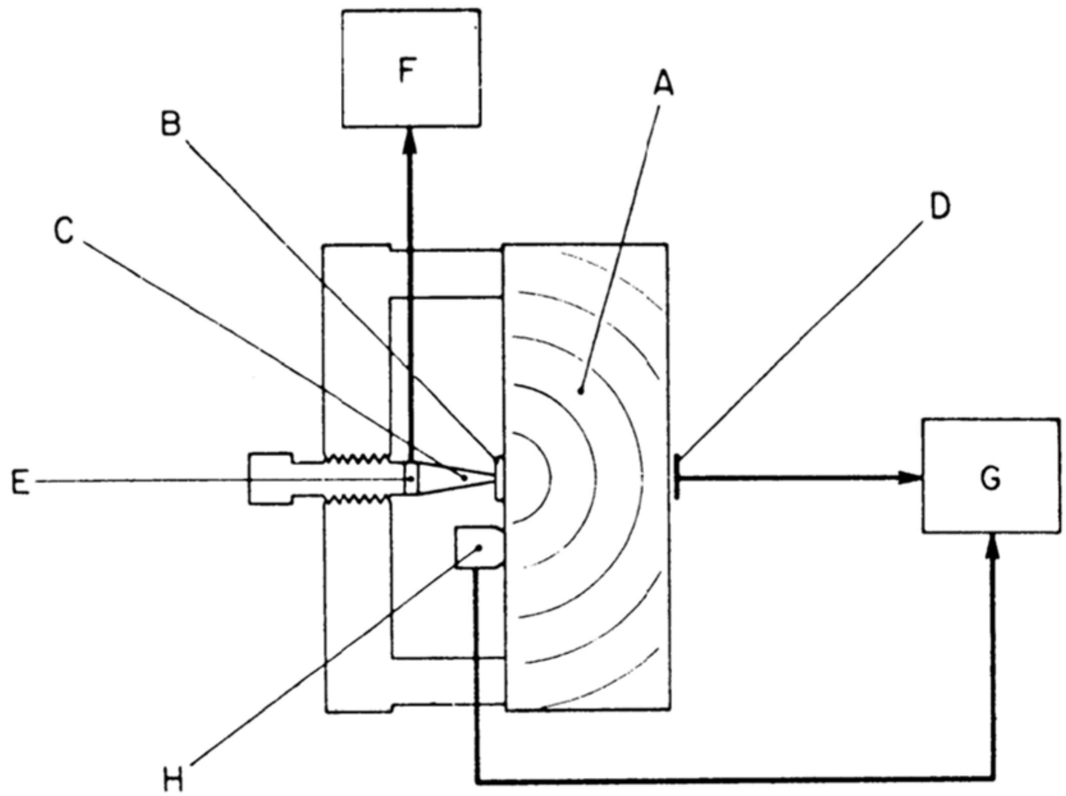


Fig. 10. Schematic of set-up for recording of acoustic-emission signatures uncontaminated by ringing of specimen: A, transfer block; B, test sample; C, indenter; D, transducer; E, lead zirconate-titanate disc; F, charge amplifier; G, high-speed storage oscilloscope; H, trigger-signal pickup.

Figure 11 shows some data gathered in the check out of the set up. The top figure is an exact solution by Lamb[4] and it gives the surface response of an elastic half space due to a step function in applied force. The lower photo is the response as measured by the capacitance gage. While it does not give a complete quantitative determination of the characteristics of the capacitance gage, it does give one a very good indication of at least its limits of response. Work is continuing in this area in order to obtain an acoustic emission transucer calibration technique.

In closing I'd like to ask for your input to the NBS program on NDT standards. We're very interested in performing activities that you would find useful as users of NDT, and we certainly elicit your inputs.

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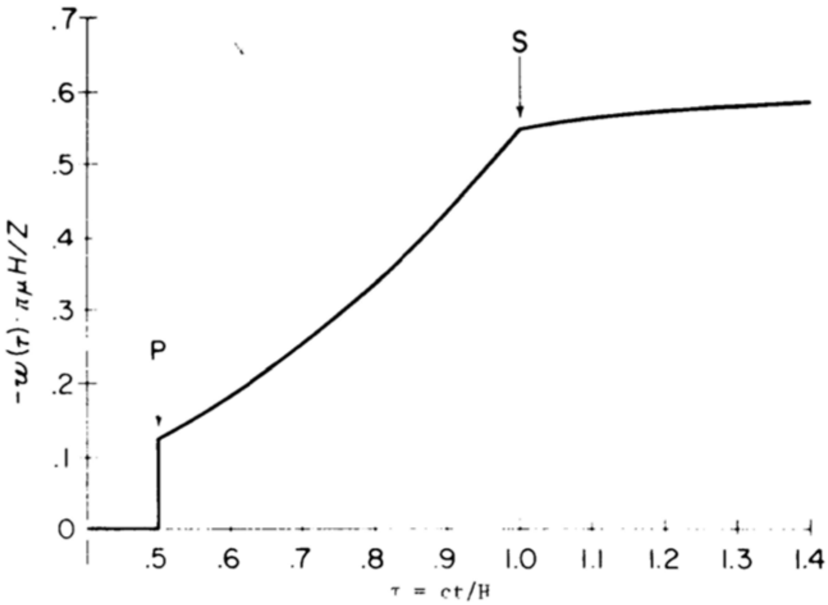
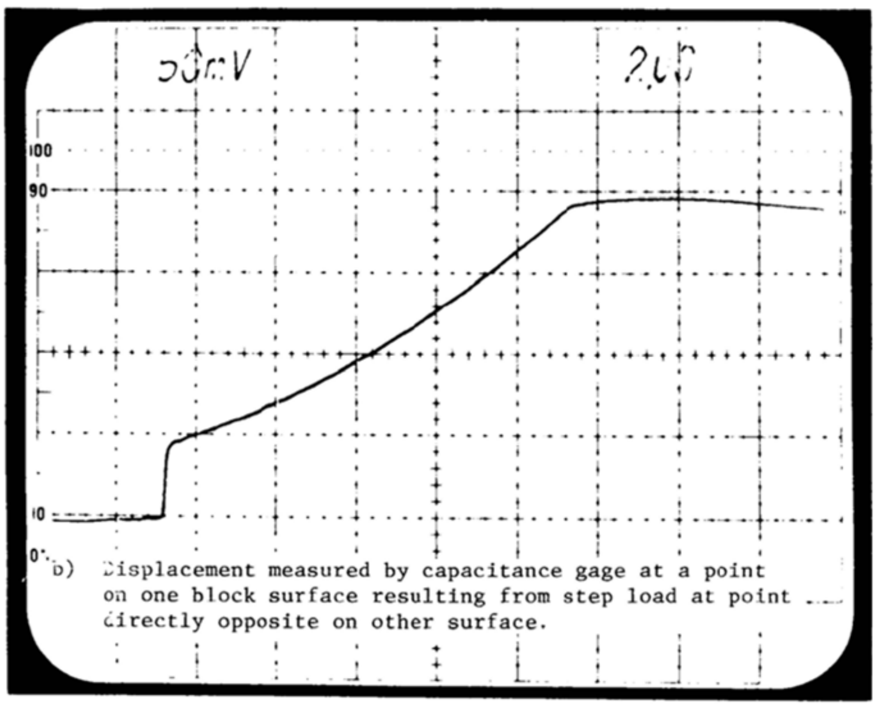


a) Theoretical displacement for a seismic buried pulse calculated from expressions by Pekeris and Lifson [5]. P and S are arrival of longitudinal and shear waves.



b) Displacement measured by capacitance gage at a point on one block surface resulting from step load at point directly opposite on other surface.

Fig. 11. Theoretical and measured surface displacements due to step force function.

DISCUSSION

DR. TOM WOLFRAM (University of Missouri): Questions?

DR. CRAIG BIDDLE (Pratt/Whitney Aircraft): In your evaluation of the ASTM blocks, I noticed that you evaluated them at 2 1/4, 5, 10 MHz and then 15 MHz. Was that the center frequency of different transducers or did you use spectrum analysis with one transducer?

DR. EITZEN: No, we used four different transducers.

DR. BIDDLE: Okay. So, those transducers also could have been off frequency or did you ever compare one 5 MHz transducer to another 5 MHz transducer, for example?

DR. EITZEN: We purchased quite a number of transducers, and, using spectrum analysis, relative power versus frequency data, and a few other measurements, we tried as best we could to choose the best ones for taking the data. The center frequencies of the ones used were rather close to the nominal numbers.

DR. BIDDLE: Once you selected a transducer for doing the work, you either stick with that transducer or you play a lot of games until you find another transducer that responds exactly the same way?

DR. EITZEN: Yes. We had to go through that recently when our 10 MHz transducer blew.

DR. BIDDLE: That's what I expected. That's what I was wondering. Have you looked at characterizing the spectrum response, regardless of the transducer, of the hole and then normalizing it?

DR. EITZEN: No, we have not.

DR. HARRIS MARCUS (Rockwell International Science Center): On your compact tension specimens, how would you be able to make standards if you expect relaxation phenomena to keep changing the crack closure? With time, that's going to change and if you use these as standards your apparent crack length will constantly change.

DR. EITZEN: Yes, I would guess that to be a problem. There are a number of problems in that area that haven't been solved yet, but hopefully the relaxation, after not too long a period of time, will diminish to the point where it's not really important anymore. In addition, we may have to use a loading program that minimizes closure.

MR. STEVE HART (Naval Research Laboratory): In connection with the one transducer you showed that came out at 23 MHz instead of 15 as labeled, I have run into the same thing, and I have a sneaking suspicion that the manufacturer has labeled them low or rather made them higher than the labels in order to allow for the fact that most people won't use them right. People put too much cable on them and they don't drive them with the proper pulse. Then you tend to get a lower frequency. I've had the experience of measuring a higher frequency than the nominal.

DR. EITZEN: That's possible. Most of the transducers we've looked at using the power spectrum technique have come out relatively close, certainly better than 8 parts in 15 anyway. We find that an error band on a 2 1/4 MHz transducer might be ± 1/4 MHz or on a 10 MHz transducer it might be ± 1 or 2 MHz, but the one shown in Fig. 9 is certainly an anamolous one compared to others we've looked at. Our sample size is still small though.

MR. STEVE HART (NRL): That one was pretty far out, that's true.

MR. TOM BERTAL (CR & D, General Electric): I just wanted to comment that typically my experience has been--and also talking with other people throughout the company--that transducers vary from the nominal stated value by ± 50 percent and it's not surprising that the values are as you show them. It is difficult to get manufacturers to change, at least GE hasn't been successful in doing that yet. The one thing that seems to be ignored in transducer construction, and probably very difficult to control, is the damping. The transducer material is nominally cut to frequency with quite a coarse tolerance and then the damping is applied, maybe a tungsten loaded epoxy or something of that nature. Depending on how that recipe was executed the transducer frequency will shift, but that shifted frequency never appears on the transducers.

DR. MIKE BUCKLEY (WPAFB): Don, could you tell us at what time you hope to have what part of your output achieved, and exactly what it will be.

DR. EITZEN: The second part I can't tell you right now but, referring to the three possible outputs I mentioned earlier, we have scheduled a decision point of October.

DR. BUCKLEY: For what?

DR. EITZEN: For deciding whether it will be a methods document, a "gold-plated" standard or a Standard Reference Materials type approach. We are still aiming for December to February for an output. If it's to be a "gold-plated" standard there's not as great a problem. If we decide in October, December seems attainable. In the case of a "gold-plated" standard it's not as important precisely what unit value you have as long as it's constant. The NBS museum has some interesting artifacts. There is a candle and holder sitting there that used to be a standard for candle power, and the only thing that made it any different than other candles and holders was that it was maintained nicely. It was kept very clean. Its value was initially, something of a free choice, but it was constant. If you decide on "gold-plate" standards, then--

DR. BUCKLEY: I guess the question is how do we get reproducible standards which means you'll have to tell people how to process them. You say there's a big error in processing and you don't yet know all the origins. Am I correct?

DR. EITZEN: Well, if you can't get reproducible standards, then you want to know what the differences are. Some people's standard mass is not 1 kg, but the difference from 1 kg is known to a very high degree of accuracy.